

Conduction and cooling flows

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ABSTRACT

Chandra and XMM-Newton observations have confirmed the presence of large temperature gradients within the cores of many relaxed clusters of galaxies. Here we investigate whether thermal conduction operating over those gradients can supply sufficient heat to offset radiative cooling. Narayan & Medvedev (2001) and Gruzinov (2002) have noted, using published results on cluster temperatures, that conduction within a factor of a few of the Spitzer rate is sufficient to balance bremsstrahlung cooling. From a detailed study of the temperature and emission measure profiles of Abell 2199 and Abell 1835, we find that the heat flux required by conduction is consistent with or below the rate predicted by Spitzer in the outer regions of the core. Conduction may therefore explain the lack of observational evidence for large mass cooling rates inferred from arguments based simply on radiative cooling, provided that conductivity is suppressed by no more than a factor of three below the full Spitzer rate. To stem cooling in the cluster centre, however, would necessitate conductivity values at least a factor of two larger than the Spitzer values, which we consider implausible. This may provide an explanation for the observed star formation and optical nebulosities in cluster cores. The solution is likely to be time dependent. We briefly discuss the possible origin of the cooler gas and the implications for massive galaxies.

Key words: galaxies: clusters: – cooling flows – X-rays: galaxies

1 INTRODUCTION

The intracluster gas at the centres of many clusters of galaxies has a radiative cooling time of a billion years or less (Peres et al. 1997), suggesting that cooling flows may be operating there (Fabian 1994 and references therein). Chandra has now enabled spatially detailed temperature profiles to be made of such cluster cores and large temperature drops, by up to a factor of three, are commonly seen (Allen et al. 2001a,b,c; Schmidt et al. 2001; Ettori et al. 2002; Johnstone et al. 2002; David et al. 2001; McNamara et al. 2001; Molendi et al. 2001). Results from the high spectral resolution Reflection Grating Spectrometer (RGS) on XMM-Newton also show temperature components down to about one third of the overall cluster virial temperature (Peterson et al. 2001; Tamura et al. 2001; Kaastra et al. 2001; Peterson 2002). It is of great importance, however, that RGS spectra do not show evidence for lines expected from gas cooling at lower temperatures (e.g. from Fe XVII).

This general result means that a simple cooling flow is not operating in cluster cores and has provoked the study of a wide range of possibilities, including absorption of the soft X-rays to mixing or heating of the cooler gas (Peterson et al. 2001; Fabian et al. 2001, 2002; Churazov et al. 2001; Böhringer et al. 2002; Brüggén & Kaiser 2001). If heating is the answer then it has to be distributed over radius and temperature and is not just concentrated at the centre (Johnstone et al. 2002).

Another process which has long been discussed for clusters is thermal conduction (see e.g. Takahara & Takahara 1979; Tucker &

Rosner 1983; Friaca 1986; Böhringer & Fabian 1989; Bertschinger & Meiksin 1986; Bregman & David 1988; Sparks 1992; Narayan & Medvedev 2001; Sugihara & Ostriker 1998). For a multi-phase cooling flow to operate conduction has to be suppressed (Binney & Cowie 1981; Fabian 1994; see Chandran & Cowley 1998; Pistinner, Levinson & Eichler 1996; Malyskin 2001 for possible mechanisms). Some observational evidence for highly suppressed conduction (Ettori & Fabian 2000) comes from the ‘cold fronts’ found in Chandra images of many clusters (Markevitch et al. 2000; Vikhlinin et al. 2001; Mazzotta et al. 2002). The serious problem relevant to cooling flows here is that conduction works best at high temperatures and cooling at low temperatures, so it is difficult to see how they can balance throughout the (observed) range of temperature (Bregman & David 1988; Fabian, Canizares & Böhringer 1994).

More explicitly, for a spherical, stationary, constant pressure, cooling flow the energy equation is

$$-\frac{\dot{M}}{4\pi r^2} \frac{d}{dr} \frac{5kT}{2\mu} = -n^2 \Lambda + \frac{1}{r^2} \frac{\partial}{\partial r} \left(r^2 \kappa \frac{\partial T}{\partial r} \right) \quad (1)$$

where n , T , μ , Λ and κ are the gas density, temperature, mean molecular weight, cooling function and thermal conductivity, respectively. If there is no flow ($\dot{M} = 0$) and $\kappa \propto \kappa_s$, the Spitzer conductivity ($\kappa_s \propto T^{5/2}$), then since $\Lambda \propto T^\alpha$, $T \propto r^{2/(11/2-\alpha)}$ (Fabian et al. 1994). So, where bremsstrahlung cooling dominates (above $T \sim 2$ keV) and $\alpha \sim 0.5$, then $T \propto r^{0.4}$ (below

$T \sim 1$ keV, where line cooling dominates and $\alpha \sim -0.5$, then $T \propto r^{0.3}$). Such a gradient is similar to those found from the Chandra images (e.g. Johnstone et al. 2002). This in no way proves that conduction operates but encourages further investigation. Narayan & Medvedev (2001) and Gruzinov (2002) have recently noted, using published results on cluster temperatures, that conduction suppressed by a factor of a few below the Spitzer rate will have a significant effect on cluster cooling flows.

Here we carry out a detailed study of the heat influx needed to balance the radiative energy loss in a low temperature cluster (Abell 2199; Johnstone et al. 2002) and a high temperature one (Abell 1835; Schmidt et al. 2001). Rather than test the hypothesis that thermal conduction is sufficient by looking at the temperature gradient at just one radius, we compute the losses and fluxes as a function of temperature and radius, as first carried out by Stewart et al. (1984). Our results show that the heat influx required to balance radiation losses occurs at a rate which is consistent with or below the Spitzer (1962) relation in the outer parts of the core (where the core is taken as the region inside the cooling radius of the cluster), but at a rate above that given by Spitzer in the very centres of the clusters. We also find that if conduction is suppressed by more than a factor of three below the Spitzer rate then heat transfer from hotter gas at large radii is unable to stop a cooling flow from developing.

If conduction is the solution to the problem of cooling flows, then it begs the question of how the cooler gas components originate. If the presence of cooler gas is due to radiative cooling of the hotter gas, then it is not obvious how such cooling has been arrested. Possibly it is due to the introduction of cooler subclusters, the dense cores of which are not thoroughly shocked (Fabian & Daines 1991; Motl et al. 2001).

2 THE TEMPERATURE AND EMISSION MEASURE PROFILES USED

Abell 2199 and Abell 1835 are relaxed clusters at luminosity distances of 187 Mpc ($z=0.0309$) and 1599 Mpc ($z=0.2523$), respectively. We assume a cosmology with $H_0=50$ km s⁻¹ Mpc⁻¹ and $q_0=0.5$ throughout.

Deprojected spectrally-determined temperature and density profiles obtained for Abell 2199 by Johnstone et al. (2002) and for Abell 1835 by Schmidt et al. (2001) were used to carry out the calculation. Briefly, photon samples extracted from annuli (eight for Abell 2199 and nine for Abell 1835) around the cluster centre were used to obtain a single (deprojected) temperature and density for each spherical shell by fitting the spectral energy distribution of consecutive annuli with multiple MEKAL (Kaastra & Mewe 1993) plasma models (one mekal model for the outermost annulus, two for the next one in, etc.) absorbed by the PHABS photoelectric absorption model (Balucinska-Church & McCammon 1992). The fitting was carried out using the PROJCT routine in XSPEC (Arnaud 1996). A more detailed description of the deprojection technique is given by Allen et al. (2001b). We note that this approach gives similar results to that of Etori et al. (2002) when tested on the same cluster. The temperature and emission measure ($EM=n^2 \times \text{shell volume}$) profiles for each cluster are shown in Figure 1.

3 THE DERIVATION OF κ

The conductivities required to balance radiative losses by conduction of heat from the outer, hotter parts of the clusters into the cen-

tral regions, where the cooling time is less than the Hubble time, are calculated using the temperature and emission measure profiles shown in Figure 1. Setting $\dot{M} = 0$ in Equation (1) and integrating gives

$$\int_{\mathcal{V}} n^2 \Lambda(T) d\mathcal{V} = \int_S \kappa(\nabla T) \cdot d\mathbf{S} \quad (2)$$

where \mathcal{V} is the volume and S the surface area of the X-ray emitting sphere.

As the data are binned into m shells, the above equation is approximated to the following sum in order to calculate the conductivity coefficient, κ_j , at the outer boundary of the j th shell,

For $j: \{1 \leq j \leq m\}$

$$\sum_{i=1}^j EM_i \Lambda_i = \kappa_j \times \left(\frac{\Delta T}{\Delta r} \right)_{(j+1)-j} \times 4\pi r_j^2 \quad (3)$$

where $EM_i \Lambda_i$ is the rate of energy loss from the i th shell, r_j is the radial distance to the outer boundary of the j th shell and $\Delta T_{(j+1)-j}$ and $\Delta r_{(j+1)-j}$ are the temperature difference and radial distance between the centres of consecutive shells, respectively.

Models were fitted to the temperature profiles in order to calculate the temperature gradient between shells. This ensures that the temperature always decreases towards the cluster centre and enables us to handle the uncertainties in our calculation. Taking the temperature difference between consecutive data points does not always provide meaningful results since several of the error bars overlap, allowing the possibility of negative temperature gradients and zero gradients, the latter consequence leading to infinite error bars on the computed conductivity values.

The cooling function was evaluated using MEKAL (with an abundance relative to solar of 0.4) and the conductivity values computed using Equation (3) plotted against the temperature given by the model at r_j . Only shells lying within the cooling radius of the cluster were used to compute κ ; $r_{cool} \sim 150$ kpc for Abell 2199 (Johnstone et al. 2002) and $r_{cool} \sim 200$ kpc for Abell 1835 (Schmidt et al. 2001). The results were compared with the conductivity-temperature relation given by Spitzer (1962).

The thermal conductivity of a completely ionized gas in a space free from magnetic fields and for which the ions are all of one kind (hydrogen) is given by Spitzer (1962) as

$$\kappa_s = \frac{1.84 \times 10^{-5} T^{\frac{5}{2}}}{\ln \Lambda} \text{ erg s}^{-1} \text{ cm}^{-1} \text{ K}^{-1} \quad (4)$$

where $\ln \Lambda$ is the Coulomb logarithm (see Cowie & McKee 1977). The accuracy of this equation does not exceed 5-10 per cent (see Spitzer & Härm 1953). For electron densities and temperatures appropriate to the clusters considered, $\ln \Lambda \sim 37$, and

$$\kappa_s \simeq 5.0 \times 10^{-7} T^{\frac{5}{2}} \text{ erg s}^{-1} \text{ cm}^{-1} \text{ K}^{-1} \quad (5)$$

In a plasma with magnetic fields the conductivity may be reduced by a factor of three or more below the Spitzer value (Narayan & Medvedev 2001; Malyshkin 2001).

Simple power law fits to the deprojected data are shown in Figure 1 ($\chi^2_\nu \sim 6.6$ for Abell 2199 and $\chi^2_\nu \sim 2.3$ for Abell 1835). Using these models we find conductivity values which scatter around the Spitzer curve (see Figure 2). However, the reduced chi-square

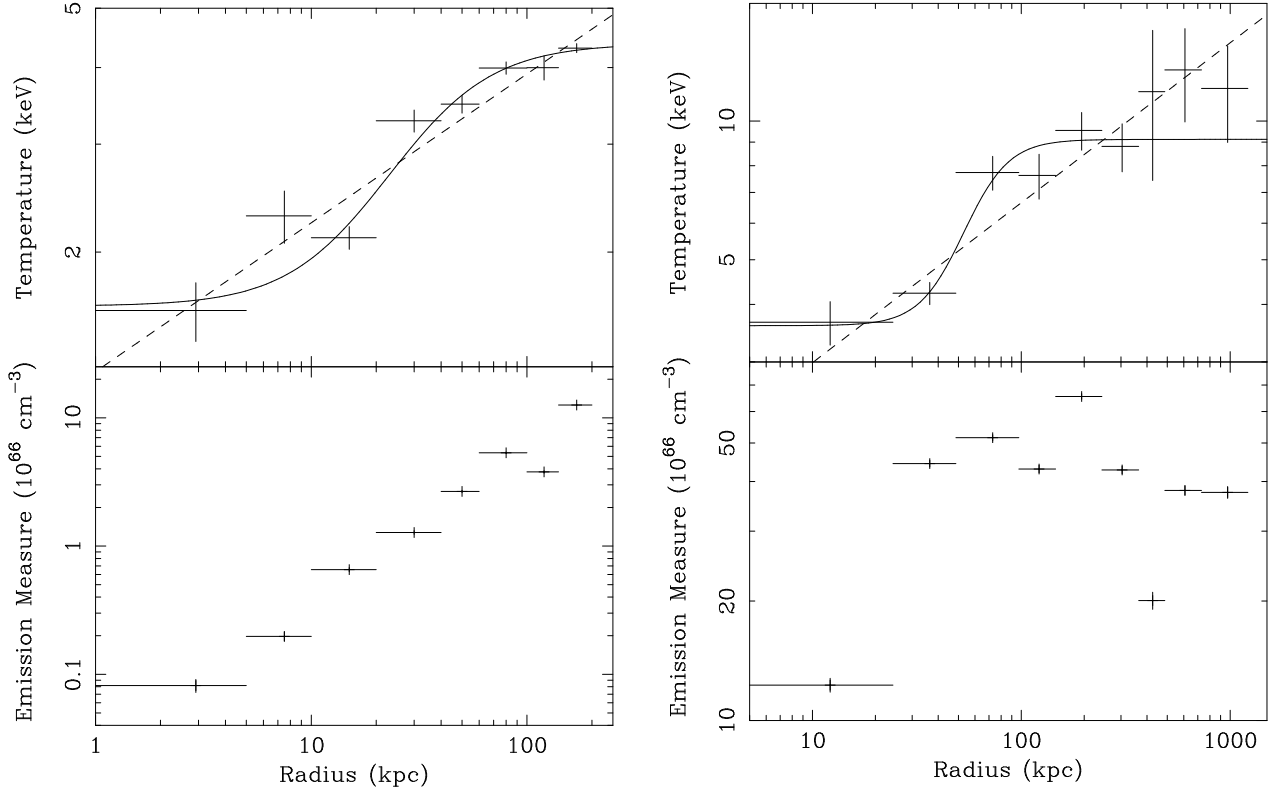


Figure 1. The observed (deprojected) spectrally-determined temperature and emission measure profiles for Abell 2199 (left; Johnstone et al. 2002) and Abell 1835 (right; Schmidt et al. 2001). The one sided error bars plotted (necessary for chi-square calculations) are the root-mean-square of the two sided error bars given in the aforementioned papers. The dashed lines are the best fit power laws to Abell 2199 ($\chi^2=39.5$, 6 degrees of freedom) and Abell 1835 ($\chi^2=16.4$, 7 degrees of freedom). The solid lines are the best fit curves to Abell 2199 ($\chi^2=12.3$, 4 degrees of freedom) and Abell 1835 ($\chi^2=5.5$, 5 degrees of freedom) using the functional form in Equation (6).

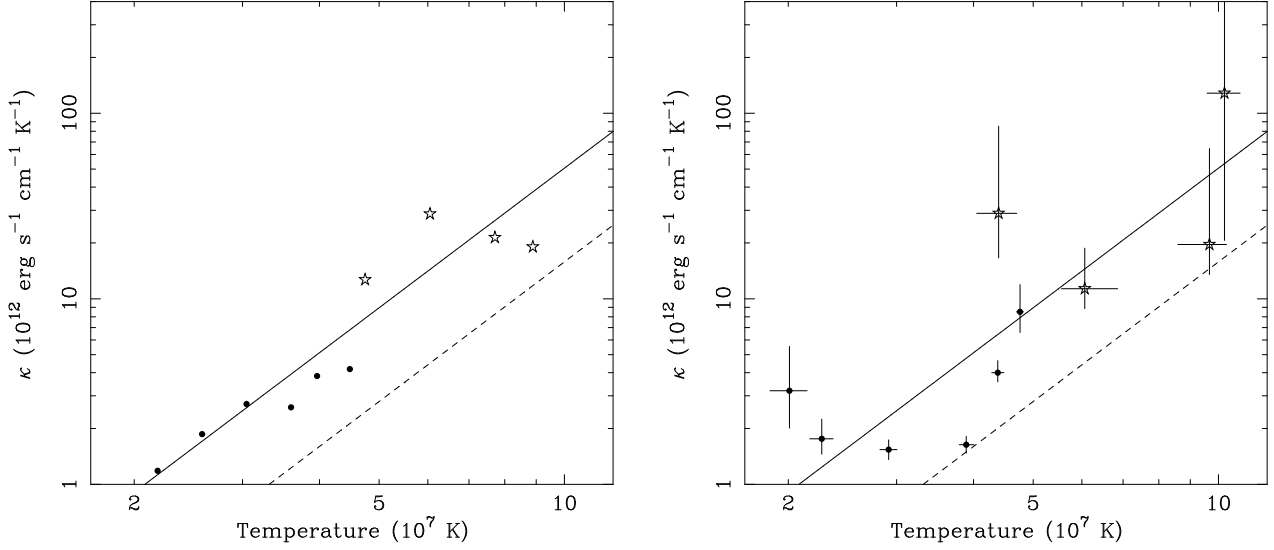


Figure 2. The conductivity coefficients required for conduction to balance radiation loss using power law fits (left) and using the functional form given in Equation (6) (right) to the temperature profiles. Filled circles represent the results for Abell 2199 and open stars for Abell 1835. The upper error bar on the fourth data point for Abell 1835 is $4.9 \times 10^{15} \text{ erg s}^{-1} \text{ cm}^{-1} \text{ K}^{-1}$. The solid line is the Spitzer conductivity and the dashed line is one third of the Spitzer conductivity.

value of the fit to the temperature profile of Abell 2199 is unacceptably high. We therefore looked for a model which provided a better reduced chi-square for both cluster profiles.

The temperature profiles were modelled using a function of the form

$$T_r = T_0 + T_1 \left[\frac{\left(\frac{r}{r_c}\right)^\eta}{1 + \left(\frac{r}{r_c}\right)^\eta} \right] \quad (6)$$

where T_r is the temperature at a radial distance r from the cluster centre. Allen et al. (2001b) use this model as a reasonable universal fit to projected temperature profiles of six cooling flow clusters, including Abell 1835. We adopt it here for the deprojected temperature profiles as a smooth fitting function. T_0 , T_1 , r_c and η are free parameters determined using chi-square fitting.

The best fit models to the temperature data are shown in Figure 1. For Abell 2199, $\chi^2_\nu=3.1$ ($kT_0=1.6$ keV, $kT_1=2.7$ keV, $r_c=30.1$ kpc, $\eta=1.8$) and for Abell 1835, $\chi^2_\nu=1.1$ ($kT_0=3.6$ keV, $kT_1=5.5$ keV, $r_c=59.3$ kpc, $\eta=4.1$). The probabilities of exceeding the chi-square values are 0.02 and 0.35 for Abell 2199 and Abell 1835, respectively. Although the fit to Abell 2199 is only marginally acceptable, this function provides much improved reduced chi-square values over the power law fits.

The physical motivation for using these models must also be considered. Both clusters contain radio sources and as such are not expected to have temperature distributions which are smoothly increasing functions of radius. It is likely that the profiles are time-dependent, undergoing fluctuations from a smooth curve during radio outbursts lasting $\sim 10^7$ years. Since conduction must operate on timescales $\sim 10^9$ years in order to successfully offset cooling, this calculation requires the time-averaged cluster profiles. We reason that as the functional form used here is a fair representation of several cooling flow clusters, it is a plausible time-averaged model. It is certainly more physically realistic than the power law models since it has a vanishing gradient both at large and small radii. We proceed using this function and take caution when analysing the results for Abell 2199.

Conductivity values and corresponding 1σ uncertainties were found using Monte Carlo simulations. Ten thousand random temperature profiles consistent with the data were generated and fitted using a chi-square minimization routine. The median conductivity and temperature value at each radius are plotted in Figure 2, with the central 68 per cent of each distribution providing the error bars. The emission measure errors are negligible in comparison.

In both clusters we find conductivity values which are less than a factor of three below the Spitzer curve in the outer regions and which lie above the curve in the innermost regions. The latter result shows that conduction at the full Spitzer rate is insufficient to balance cooling in the centres of Abell 2199 and Abell 1835. Whether the higher conductivity required for the hottest, outermost points is important depends on the age of the cluster. We used the temperature difference given by the model between shell centres, rather than the derivative at the outer boundary of each shell, so as not to rely on the model too rigorously. It is reassuring that simple power law fits to the data confirm the requirement for conduction at a rate greater than the Spitzer rate in the lowest temperature regions.

4 DISCUSSION

We have shown for Abell 2199 and Abell 1835 that heat conduction at a rate close to the Spitzer rate is sufficient to balance cooling in the outer regions of the core. However, if conductivity is suppressed below the Spitzer rate by more than a factor of three, as is possible in a plasma with a tangled magnetic field, heating by conduction merely reduces, but cannot prevent cooling. This result is clearly dependent on the value of $h = H_0/100 \text{ km s}^{-1} \text{ Mpc}^{-1}$, since $\kappa \propto h^{-1}$. Thus the lowest value we find for κ at about one third the Spitzer rate drops to one fifth that rate if $h = 0.75$. (In principle, if we can accurately predict the value of κ and can assume that conduction balances radiative cooling then we have a new method for determining H_0).

Towards the innermost regions conduction at the full Spitzer rate is unable to offset cooling, implying that, in the absence of an additional heat source, a small cooling flow will operate in the central (10-20 kpc), cooler parts of the cluster cores. We consider this likely, given the possibility that the solutions to the energy equation (1) are unstable (Fabian et al. 1994). Observationally, many of the Chandra and RGS limits allow for a small but significant flow (e.g. McNamara et al. 2000; David et al. 2001; Allen et al. 2001a,b; Peterson et al. 2001; Peterson 2002), which can supply the observed star formation and optical nebulosities (Johnstone, Fabian & Nulsen 1987; Heckman et al. 1989; Allen 1995; Cardiel et al. 1998; Crawford et al. 1999) and cold gas (Edge 2001 and references therein). We note that the radius of the inner region where the required conductivity exceeds the Spitzer value coincides with the apparent break in the \dot{M} profiles found from a cooling flow analysis of the data (Schmidt et al. 2001; Johnstone et al. 2002).

Given the opposing temperature dependences of conduction and cooling, further work is required to show whether initially isothermal regions can develop the large, central temperature gradients observed. The cooler gas may be a remnant of earlier subclusters, the dense cool gas cores of which have only partially merged with the main cluster. The situation is time-dependent. The cold fronts first reported by Markevitch et al. (2000) and the transonic motion of some of the gas (Vikhlinin et al. 2001) are evidence for this scenario. Presumably conduction is highly suppressed across a moving front, due to organised magnetic fields, but may rapidly set in at the rear when the gas is decelerated. A radial field will, of course, be optimal for conduction. Such a field could be the consequence of a cooling inflow (Bregman & David 1988).

Much further work on a wider range of clusters is required to test the conduction hypothesis. It will be most interesting if a simple physical process such as conduction is responsible for limiting the total cooled gaseous mass of the largest galaxies. It will also be interesting to investigate whether conduction is operating in the interstellar medium of elliptical galaxies (Saito & Shigeyama 1999), thereby explaining why they have very short radiative cooling times at their centres, yet little evidence for cooling flows.

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